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Robotic Solution for the Automation of E-waste Recycling

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ABSTRACT– This paper focuses on the issue of e-waste and the use of a 6 Axis Robotic manipulator to build and test an industrial robotic system to detect components of commonly disposed of E-waste, then disassemble and segregate the main components for proper disposal and recycling using OpenCV image capture, TCP connections between OpenCV and ESPON, Arduino integration for Servo control and 3D Printed fixtures for disassembly.

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Introduction

This paper will focus on the use of Robotics and Robotic system integration to try and find an answer to the issue of e-waste recycling. One of the fastest-growing waste categories in the world is e-waste, this is waste that is created from used electrical and electronic equipment. This is growing at a rate of 3–5% per year [1]. A report by the 2020 Global E-waste Monitor has estimated that 53.6 million metric tonnes of e-waste were created in 2019. That represented a 21% jump in the five years since 2014. In 2021 the waste generated was 57.4m tonnes and with e-waste on a predicted course to reach 74m tonnes by 2030. This increase is attributed to higher consumption rates of electronics, limited repair options and shorter product lifecycles [12]. The world's population is growing, increased disposal of end-of-life electronic products that are linked to the ever-increasing number of electrical items has caused serious concerns for the environment. The growing issue of electronic waste is due to the vast quantities and the rate at which it is being generated has increased exponentially over the last five years, this is set to continue to grow at a rapid rate. Advances in technology and working from home due to COVID-19 means electronic manufacturers are releasing more new devices to serve the consumers and this has contributed to the increase in e-waste [4]. This represents a major challenge for the world due to the cost and environmental impacts this causes.

E-waste can be classified as hazardous waste, but unlike other categories of waste, e-waste also has substantial potential in monetary value. There was an estimated 57 billion US dollars of secondary raw materials present in the total e-waste that was generated in 2019 [2]. With such a huge value locked in e-waste, the recovery of secondary materials is important to consider and to try and conserve the primary raw materials that are being depleted at an alarming rate. It has been estimated that in one metric ton of personal computer wastes there is more gold than in 17 tons of gold ore [3]. In 2016 only 20% of the worlds e-waste was properly recycled, and the remaining 80% was unknown [1]. In 2019 about 17.4% or 9.3m tons of global e-waste was collected and recycled, with the balance of 44.3m tons or 82.6%, unaccounted for [3]. The main challenge for managing e-waste is its massively high volume and complexity. Compounding the difficulty in separating e-waste components is that the mode of construction is different by product and manufacturer. Despite many challenges, e-waste recycling offers multiple opportunities owing to its huge richness of resources and its role in limiting the pace of e-waste disposal and recycling [4].

Related Research

E-waste is one of the fastest growing waste categories of waste in the world, with e-waste on a predicted course to 74m tonnes by 2030 [12]. Figure 1 shows the projection of E-waste up to 2030. E-waste covers a broad range of electronic devices, ranging from large household appliances, IT, lighting, medical devices, monitoring and control instruments to consumer electronics and mobile phones. Four key global issues make e-waste a priority waste stream, specifically: global quantities of E-waste, impact on global resources, health and environmental impacts and moral concerns [2].

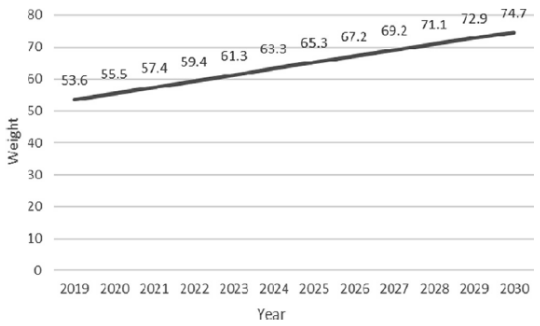

Figure 1. WEEE generation from 2019 to 2030. 2020 onwards are projections [2]

COVID-19 has led to the removal of many certainties that are taken for granted resulting in severe economic shock and social issues throughout the world. At the same time, humanity is called upon to find solutions and to seize opportunities in a background where threats and risks seem to triumph. This has resulted in an explosion of requirements for technology and in turn electrical and electronic components to try and overcome these crises through digitisation, whether through remote working, learning or improvement in productivity with the IoT. The relationship between sustainability and resilience is the underpinning of what is able to be implemented with good practices and strategies to enable a reduction of waste generation as well as an approach based on prevention, reuse, recycling and recovery of waste [7]. Electrical and electronic equipment such as mobile phones, tablets, televisions and coffee machines that make life more comfortable and luxurious have become an essential part of modern life. However, short lifespans, limited repair options and fast-changing technology is turning a high proportion of electronic gadgets into waste at the end of its usable life due to damage, operational risks, or availability of better and newer alternatives, such as the latest mobile phone, tablet or laptop [3].

Challenges of E-Waste

One of the main challenges in managing e-waste is its enormously high volume and complexity. The difficulty in separating e-waste components is due to the fact parts and sub components are constructed in many diffident ways with different manufacturing techniques. Some are bolted, others screwed, snapped, glued or soldered together. As households tend to dispose of all categories of e-waste together, this makes it difficult to segregate e-waste components into different categories such as plastics, metals, and glasses to be effectively recycled into different specific product groups. Despite these challenges recycling e-waste offers many opportunities owing to the availability of resources e-waste contains and its role in limiting the pace of e-waste generation that ends up in landfill or incinerator contaminating the environment [3].

E-waste contains a variety of organic and inorganic pollutants such as heavy metals, polycyclic aromatic hydrocarbons (PAHs). Recycling without suitable measures to limit the environmental pollution can cause these to leak into the ecosystem which can adversely affect human health. This exposure to toxins and their toxicity can lead to health issues in e-waste workers and the population nearby to sites of e-waste recycling [4]. Due to the shorter lifecycles of these electronic products, the recovery of valuable metals from e-waste is of economic value. Challenges in managing electronic waste arise from a lack of technical skills, poor infrastructure, inadequate financial support and inactive community engagement [5]. E-waste contains substances of which many are toxic, this creates serious pollution upon disposal [6]. The risks associated with e-waste management also need to be understood, there are risks to personal data from cyber security in the collection phase, during the transportation there are environmental risks and during processing economic risks, however recycling dose pose less risk overall as comparted to the alternative of landfill [7].

It has been estimated that the number of IoT devices will have exceed 30 billion by end of 2020. End of use (EoU) and end of life (EoL) management of IoT electronic devices can possibly result in security threats personal and data theft, which brings to the front concerns about data theft and other forms of cyber-crime. With more electronic devices becoming smart and IoT-enabled, unauthorised access to and the usage of personal information is a major concern. Theft and unauthorised access to personal information is on the rise [2].

Recycling of E-Waste

There are a number of recovery options for WEEE including reuse, repair, recycling and remanufacturing. Recycling is the process of recovering material content of used and non-functioning products through a series of processes, such as disassembly, sorting and segregation. To determine the methods to process the different types and quantities of e-waste is an important operational decision for recycling. As e-waste is of a mostly unknown nature and very complex with varying degrees of material content and age is it is difficult to determine these operational decisions. Due to this complication, a large degree of variability and uncertainty is expected in recycling operations of WEEE. For example, the processing times and recycling amounts of materials retrieved and components of WEEE may vary even in the same group of products, e.g., TVs. [16]. This is because there are so many different manufacturers for the same type of EEE and also the technology and material construction will change quickly and frequently due to advances in technology. E-waste has the potential of being either a resource or a pollutant. This has turned e-waste management and recycling into an important matter of research. The management is therefore difficult because besides strategic and political issues the constant change in materials used in the manufacturing of electronic equipment requires constant updates concerning legislation and up-to-date recycling processes and recovery technologies [19]. One of the solutions being explored is that of human–robot collaboration, this relies on only assigning the tasks that require human skills to be performed and sending all other tasks to robots.

This type of collaboration could also bring additional benefits to the environment, an example is through higher recovery rates of materials in shorter process times. Shopfloor workers could then get to decide on the decisions within the factory to enjoy a better working environment with higher levels of safety and to avoid the more dangerous tasks. This is because e-waste contains many dangerous materials such as

cadmium, lead, mercury and other flame retardants, that must be separated and treated, which suggests consumer mindfulness to then return e-waste to distinct collection points. Once end-of-life products are recycled, valuable materials that are recovered can be reintroduced into the marketplace as secondary materials, thereby extracting value from them and reducing the need for new materials [20].

Robotics in E-waste

The Telegram application is used as a communication device for the user side by sending data in the form of FFT conversion results, temperature and other vibration data. Telegram is a messaging app with a focus on speed and security that works really fast and simple. Telegram can be used on Smartphone devices at the same time where the messages can sync seamlessly across a number of phones.

Basically Telegram, can send messages, photos, videos and files of any type like doc, zip, mp3, etc sent by individuals or systems. Sending messages from ESP8266 equipment is done by installing the Telegram Bot library then initializing it with the Bot Token requested via the Telegram server with the Telegram Bot bot syntax (BotToken, net_ssl), where net_ssl is a variable for wifi. Next, initialize the Bot with the bot.begin() command. Receiving messages from outside is done with the command message m = bot.getUpdates(), while sending data to Telegram users is used via the command bot.sendMessage(chat_id, text), where chat id is the intended Telegram id and text is the message to be sent. In this study, the text variable is filled with the detected sensor parameters, namely: temperature and frequency of the results of the FFT transformation.

Results and Discussion

The classification and dismantling of E-waste are very challenging, this is because of the vast variances in the construction of EEE that makes the recycling process almost impossible to fully automate. A fully manual process has the issue of its high cost due to the high labour content as well as the hazardous elements in e-waste resulting in HSE risks that need to be lessened. The prospect of a semi-automated process could be a possible solution as the process could be modified to the condition of the electronic equipment, therefore enhancing flexibility. The use of collaborative robots is connected to industrial robots that work together with human workers in the same workspace but are separated by light beams or fences to jointly perform the tasks. Human–robot collaboration has generated a lot of interest, however real applications in industry are still rare. Using collaborative robots, tasks that are deemed to be dangerous and repetitive can be allocated to robots, leaving the more interesting actions to humans. As a result, accidents in the shop floor can be lowered, productivity increased, and as a result greater job satisfaction can be attained by human workers. There continue to be many aspects related to human–robot interaction and collaboration that remain difficult with issue relating to safety, liabilities and legal. These are important issues that needs to be addressed in order to provide robotic support to humans in many working related areas, such as assembly and disassembly [25].

The awareness of such transfer operations requires that the robot is able to create actions that are suitable in terms of timing, kinematics, etc. In the assembly process, the choice of introducing a robot for an automation task is based on both qualitative and cycle time criteria. This is because the main objective is to finish a product in an efficient way, on time with zero defects. However, in recycling the priorities are different, there are no due dates, the arrival time of disposed devices is very difficult to forecast, and components may not be easily recognized as they may be broken or damaged.

Automation of E-Waste

There are some tasks that may be too complex to be performed by robots or just too expensive to be automated as they may require special tools or jigs and fixtures to be engineering and new systems developed. Consequently, a collaborative environment in which humans and robots can work together and share tasks in a fenceless and open environment is a suitable goal to aim for. Safety and interaction are key success factors for this idea of collaboration between humans and robots. On the one hand, the safety of human beings around the robot must be guaranteed during the execution of tasks. As physical safeguards may be impractical for true cooperation, the use of either force or speed limiting and separation monitoring is possible. Another approach is the robot must be constantly aware of what is happening around it to monitor the actions of the workers in order to change its behaviour such as the speed and trajectory according to the distance separation [23]. Therefore, the use of Collaborative robots helps to mitigate these risks and separations by allowing the robot and the human to work closely with one another in the same working evolve without the need to fences, gates, tactile floors and light curtains.

Disassembly process in E-waste recycling

Disassembly currently is a labour-intensive process with minimal automation. The reason is that disassembly usually has to address different model variations from different brands, physical uncertainties due to component defects or damage during usage, and incomplete product information [30]. The assembly process usually is unique, the assembly line is designed by a work-cell layout with consecutive work stations and special fixtures to keep the orientation of the part to be disassembled. These repetitive tasks process is usually done by robots which are programmed. On the other hand, the disassembly process becomes a lot more challenging due to a number of reasons. This could be that a variety of different electronic wastes may be put on the same disassembly line to reduce the cost of building separate lines, and disassembly is usually performed incompletely for collecting valuable components only. The products that are to be recycled may contain components that have hazardous substances and need to be handled carefully. Parts to be disassembled may be placed on the disassembly line with mixed orientations and because of that, the robot may perform unnecessary paths in order to reach the designated first task. Therefore, the disassembly process is mainly performed by humans instead of an automated disassembly line. It is also necessary to have the knowledge of the part that is to be disassembled, including the condition and locations of its components before generating the disassembly sequences for that type of products. If the location and the conditions cannot be identified, the robot cannot locate the component that is to be disassembled or the human operator may unknowingly proceed with the task that

is unsafe, potentially resulting in a failed sequence or even safety issues in the disassembly line [31].

The application of robotic disassembly in industry is currently limited due to technological constraints on handling uncertainties in product variation and conditions in end-of-life products. A system that is robust needs to be able to overcome uncertainties such as system inaccuracy and varying product conditions [32]. While non-destructive disassembly is preferable to preserve the components, this tends to require more specialized tools and is more prone to error since they rely on the integrity of part shapes and surfaces. On the other hand, semi-destructive actions are more versatile and robust such as cutting. Semi-destructive disassembly may involve damage to fasteners but not main components [32]. A mix of tooling is desirable to allow the system to take advantage of the benefits of both destructive and non-destructive techniques.

Developing flexible robotic systems that can be used in many different types of products that can handle uncertainties remains a significant challenge for AI and vision research. The task of un-screwing, a popular option is to use powered tools or wrenches that are mounted on the robot end effectors. During the disassembly process, unbolting comes with orientation and or positional uncertainties that is due to the initial assembly sequence or in-life usage and abuse. Over time the shape and size of the bolt or nut might change, due to reasons such as force, friction and temperatures. As a result, the threads might become distorted and damaged. Different methods have been pushforward to tackle these uncertainties of unscrewing, these are using advanced machine vision and algorithms, develop special-purpose tools or by proposing a robotic framework that is sequential in nature. Evenson, the main problem still exists, that is obtaining a generalised approach that can handle bolts, nuts and parts with a variety of sizes and thickness that can accomplish the assigned task with good positioning accuracy [33].

System Overview

To design an industrial robotic system to address the challenges of E-waste recycling for household items, such as smoke detectors, radios, remote controls. This was done by developing, testing and evaluating a robotic industrial manipulator to disassemble house hold electrical e-waste into a semi-automated process and segregate the main components for proper disposal and further recycling to reduce the time, cost and health and safety impacts of recycling e-waste. Figure 2 below shows the system configuration and figure 2 shows the OpenCV, Arduino and Servo Motor block diagram. The solution will have 2 main parts. First, the robot with jig for holding the E-waste and the end effector with custom 3D printed tool and servo motor specific for the task for un-assembly along with waste segregation bins. The 3D tool and jigs were designed in Solidworks and then sliced and printed with Ultimaker 3D printer, the jig once tested was then made from a steel block for stability and durability. The second part is the computer vison, coding of OpenCV, ARDUINO, Epson RC and sending the real-world coordinates of the detected screws over the LAN connection to Epson to unscrew and then un-assemble. When a part is placed in the holder the system will capture an image and work out the real-world coordinates for specific points on the object, in this cast the 4 screws, then send these x, y coordinate data points to the EPSON over the TCP/IP connection through the python program by using the clientSocket function in Python. The Robot will then receive these coordinates through a program that sets the Epson as the server to receive data using the ParseStr and token functions to store and process the x, y coordinates in sequence. Once received, the Robot will move to the coordinates and through a set sequence of tasks then un-assemble the e-waste and place in the segregation bins.

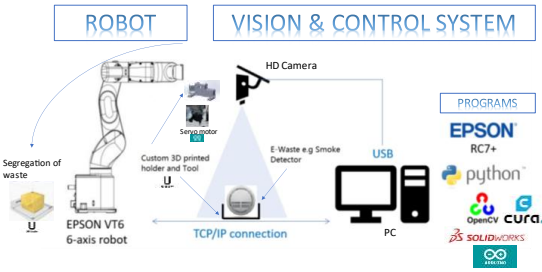

Figure 2. System Configuration

The computer vision will use OpenCV, this is an open-source computer vision and machine learning software library. The HD camera will be placed above the work piece (e-waste) and take an image capture, from this the real-world x, y coordinates from the camera x, y coordinates (see figure 5) will be worked out. This is done by calibrating the pixels to known real world coordinates and then with a mathematical formula as shown below to convert these to the world coordinates, where 'i' is the y variable coordinate from the camera.

```
pix_y = -498.798- (i[1]-
164)*(105.266/680)+33.847
        vt6_x = pix_y
        print ("vt6 x" , vt6_x)
```

The Industrial manipulator used was the EPSON VT6, this is a 6-axis industrial robot with a pneumatic gripper that has an attached custom 3D printed tool to help un-assemble the e-waste as the pneumatic gripper itself has limited flexibility, such as undoing screws. By using ARDUINO and a continuous Servo Motor linked to the I/O output of Epson, a motorised electric screw driver for unscrewing the screws can be used. The servo motor is a 360 Degree with a speed of 0.14sec/60 degree and a torque 15kg.cm. The torque required to unscrew is much less than this as they are small screws with minimal thread engagement. Once the parts have been removed, they will be placed in segregation bins for further recycling.

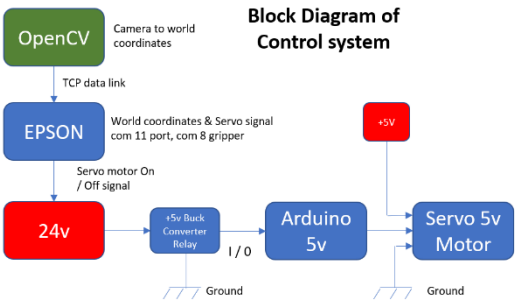

Figure 3. Block Diagram of the Arduino and EPSON interface

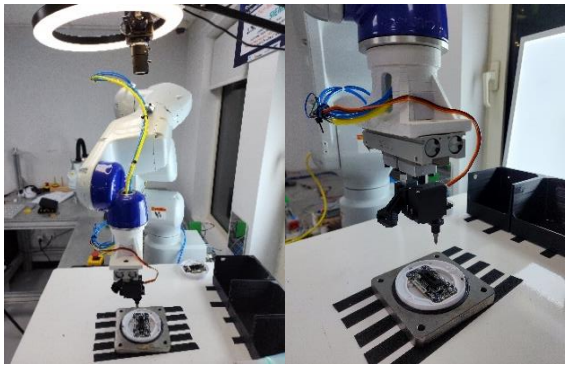

Figure 4. Pictures of the robot system with work piece, camera, lighting and cabling.

The first sequence is to first remove the plastic round filter on top of the detector, then capture the image in OpenCV and detect the 4 screws, send these to Epson along with the command to start the servo motor then once the 4 screws are unscrewed the robot will then move to and pick up the screws and put in the recycling bin for metal parts, then the electronic board is removed by the robot and placed in the bin for electronic components.

Result

The results from this experiment show that the overall project was successful in a proof-of-concept idea for using a robot to assist with the disassembly of e-waste items in a collaborative way. Humans load the part into the jig and the robot then detects and unassembled the part. The system could perform the function to detect and disassemble the material. The ability to unscrew is a major challenge, but allowed the system to function successfully. Despite many challenges in positioning, image capture, calibration and equipment, the process of capturing points to guide the process of disassembly was proved as well as the ability to make jigs and fixtures to aid this process. Figure 5 shows the output of the OpenCV image capture using the HoughCircles to find and detect the 4 screws, from this the centre of the circle is calculated. Once these coordinates are known then a calculation was done in Python based on the calibration to find the pixel to real world conversation. The robot is successful in locating the 4 screws (see figure 7) and through a count sequence based on the 4 sets of x, y coordinates move to and unscrews all 4 screws. If the part is moved in a rotation manner in the jig the robot will always be able to find and locate the screws to un-assemble the screws.

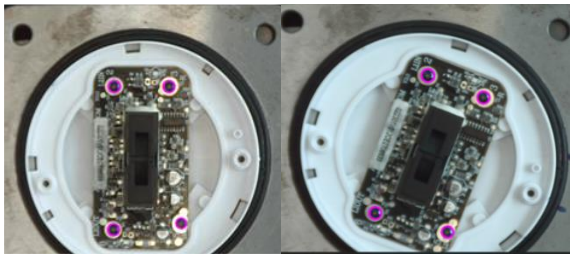

Figure 5. OpenCV image capture of the screws and coordinates in different rotations.

vt6 x	-493.444347	-549.25419411
vt6 y	119.35873887	152.54740356
centre coordinates	(556, 350)	(340, 706)

Figure 6. Coordinates of one of the screws with pixel and world

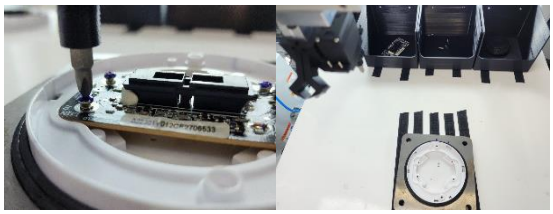

Figure 7. Screw position after receiving the coordinates and final un-assembled detector with parts in the bins.

The filter, screws and detector were then placed by the robot in the recycling bins for further processing, with the completed sequence shown in figure 7.

Discussion & Further Research

In this real-world proof of concept, the aim of this project was to focus on the more challenging part of disassembly of the internal components and develop a human / robot semi-automated system. In order to un-assemble the 3 main detector parts further work is required as the robot and pneumatic gripper are limited in its ability to pick and hold the parts. It is also too powerful and may crush some parts, a servo motor that can be controlled for torque would be better suited. Also, the detector has to be flipped 2 times to get to the internals so a rotating jig would have to be developed to do that. As such, due to system and time limitations, the process of separating the top part will be left to further research. Also, the sequence of disassembling the complete detector is challenging due to the limitations of the size of the gripper and having to flip over the part multiple times. The end effector of the robot has a 3D printed part that holds the pneumatic gripper as well as a 3D printed custom holder for the servo motor.

As a result of this during testing there was a small amount of play in the system of approx. 1mm to 2mm. As the accuracy and the repeatability required to successfully locate the middle of the screw each time needs to be high within 0.5mm, sometimes the vibration of the robot movement cause the gripper to move fractionally, this then puts the screw driver out of position and it will miss the screw as shown in figure 8.

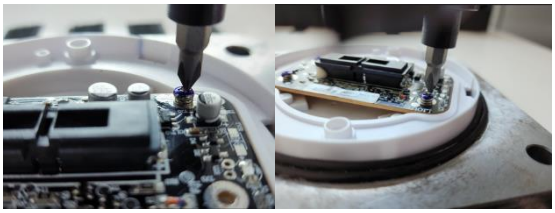

Figure 8. Positioning errors due to movements in the end effector.

For future development a machined metal part with tighter tolerances or a 3D printed metal part would offer more stability and accuracy as well as the connecting part of the gripper to the actual robot. The process time would have to be increased to make it a cost-effective option, as it takes more than 4 minutes to complete the task, but this could be increased with optimisation, quicker servo and tighter rigidity. It was also observed that the system would need a feedback system to detect if any screws where missed, else the robot would continue to disassemble the parts but would then break as it may not be completely unscrewed. This could be done by further image recognition or force sensing.

Conclusion

This project was designed to test the functionality and integration of different robotic systems to try and find solutions to the world-wide issue of disassembly of e-waste by using robotics. The gap between a very costly and complex fully automated recycling system and semi-automated system that uses both humans and robotics needs exploring further. Certainly, some tasks are very complex for robots and the issues of uncertainty and dealing with these in a robotic system is very challenging especially in the complex world of e-waste that has been described here in this paper. The methodology for the control and system set up was described in this paper along with the results on a real-world product for a real-world problem was discussed along with the challenges to over come these.

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